DOI: https://doi.org/10.59983/s2024020407
AgroEnvironmental Sustainability, 2024, 2(4), 216-233

REVIEW

Sustainability of Irrigation Practices and Water-Pricing Tools in Water-Stressed Tropical Countries: A Way Forward for Sustainable Water Governance

Tryphena Magdalene Jason [1,*], Carolin Arul [1],
Melba Respina Bakthasingh [1] and Vaishnudurga Parthipan [1]

[1] Centre for Water Resources, College of Engineering Guindy, Anna University, Chennai 600025, India
[*] Author responsible for correspondence; Email: jtrymag7@gmail.com.

ARTICLE HISTORY
Received: 18 October 2024
Revised: 02 December 2024
Accepted: 04 December 2024
Published: 17 December 2024

KEYWORDS
irrigation practices
water governance
water pricing
water stress

EDITOR
Pankaj Kumar

eISSN 2583-942X

Abstract

Increasing water stress threatens agriculture, livelihood, and sustainability in Tropical countries. Asian and Sub-Saharan African countries in the Tropical region are projected as the future hotspots of water scarcity due to rising population pressure and climate variability. Around 87 out of 180 countries will turn into 'water-stressed' and 45 countries into 'absolute water scarcity' by 2050. Irrigation water demand accounts for 70% of all freshwater withdrawals globally. Due to varying climatic, topographical, and governance conditions, the agriculture techniques in the 54 tropical countries are indigenous to the local conditions. The main objective is to review the challenges in irrigation water management in seven water-stressed Tropical countries among the 54 countries. These countries are identified based on the baseline country data mined from FAO's AQUASTAT database. A systematic literature review focusing on sustainable irrigation practices, the economic effects of water-pricing tools, and the role of policies and institutions were studied. The discussion centered on environmental sustainability, financial sustainability, institutional sustainability, and the resilience of agriculture to climate variability impacts. Community-based interventions, successful financial models, and policy and institutional reforms were perceived from successful irrigation systems. Implementation of climate-smart agricultural practices, shifting to water-saving technologies and irrigation methods, empowering the institutions, and enforcing policies and regulations to restrict resource overuse are recommended solutions for Sustainable Water Governance.

Citation: Magdalene J., T., Arul, C., Respina B., M., & Parthipan, V. (2024). Sustainability of Irrigation Practices and Water-Pricing Tools in Water-Stressed Tropical Countries: A Way Forward for Sustainable Water Governance. *AgroEnvironmental Sustainability*, 2(4), 216-233. https://doi.org/10.59983/s2024020407

Statement of Sustainability: In achieving zero hunger and ensuring food security, globally many agricultural practices that accelerate agricultural production are unsustainable, at the cost of depleting natural resources. Among all the Sustainable Development Goals (SDGs) and targets, 8 SDGs and 48 SDG targets emphasize sustainable irrigation water management. Techniques like climate-smart agriculture, managed aquifer recharging of groundwater, and shifting to cultivating less-water-intensive crops can ensure conservation of water and promote economic efficiency and social equity if the water management solutions are social-inclusive and participatory. Such policy-level and local-level interventions will aid in achieving sustainable irrigation water management.

1. Introduction

The scenario of 'Day Zero' is an alarming water scarcity concern to all developing countries worldwide, as such Cape Town in 2018 and Chennai in 2019 (Kalia, 2020). Assessing the world's hydrological cycle is significant for sustaining global food production and combating climate change (Falkenmark, 2007). Baggio et al. (2021) projected that by 2050, about 87 out of 180 countries will become 'water-stressed' with annual renewable water resources (ARWR) of less than 1700 m3/year and 45 countries in 'absolute water scarcity' (ARWR < 500 m^3/year). The water system's quantity and quality are currently under stress due to fast population growth, expansion of irrigation agriculture, industrialization, and climate change. Around the world, 70 % of freshwater withdrawals are for agricultural purposes (FAO, 2017). To sustain global food security, compared to 2000, food production will need to be increased by 70% in 2050 (Bruinsma, 2003). Therefore, irrigated agriculture plays a crucial role in global water security. Growing water scarcity can be witnessed by factors like groundwater depletion, soil loss, land degradation, rivers running dry, and increasing levels of pollution (Borsato et al., 2020). Water is the main driver of other systems such as food-production systems, climate systems, and watershed systems. The scarcity and depletion of water may hamper the socio-economic development of countries, particularly those countries which are vulnerable to climate change.

Sustainable development is defined as the development that meets the needs of the present without compromising the ability of future generations to meet their needs (Brundtland, 1987). Understanding the concept of 'strong' vs. 'weak sustainability' is vital here, as weak sustainability refers to the investment and development in one capital by depleting the natural capital, such that the net rate of change in the overall capital remains constant. Unsustainable rates of extraction of freshwater resources for irrigation are a case under 'weak sustainability' where the natural resource base gets depleted, despite the growth in food production and irrigation technologies (Streimikis and Baležentis, 2020). Borsato et al. (2020) record that globally about 40% of irrigation practices are unsustainable as they either deplete the environmental flow of rivers or the groundwater stocks. For example, in India, about 62.8% of arable land is under groundwater irrigation thereby causing over-exploitation of 14.2% groundwater units (Jain et al., 2019). Therefore, there is a need to develop sustainable production and consumption patterns in agriculture to conserve water resources for future generations.

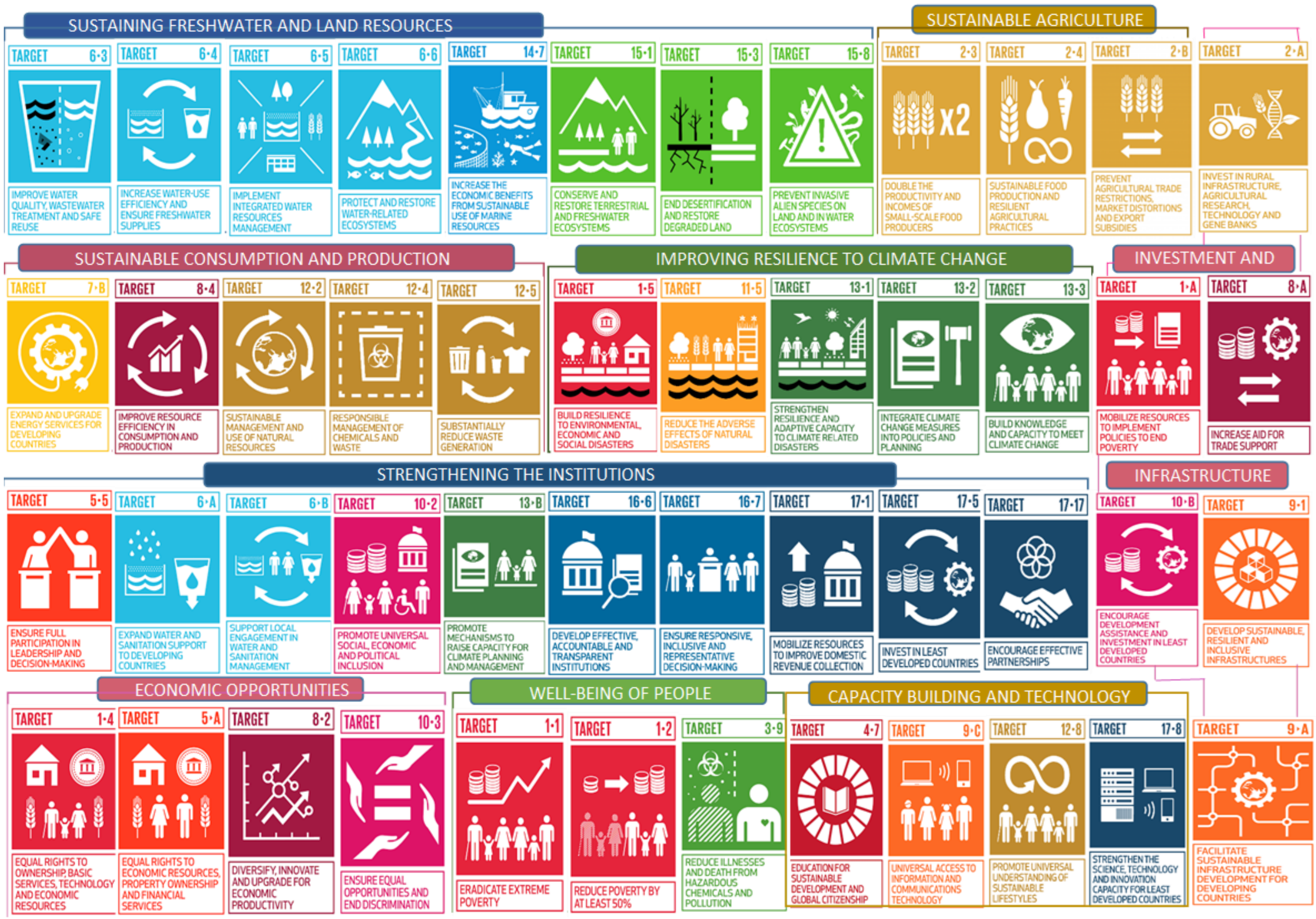

Figure 1. Sustainable Development Goal (SDG) Targets relevant to sustainable irrigation water management and water governance (Source: Illustrated by the authors based on the Sustainable Development Goals of the 2030 Agenda for Sustainable Development, 2015)

Figure 1 elaborates on the 48 relevant SDG targets that are interconnected towards achieving sustainable water management in agriculture. Sustainable solutions must include interdependence between systems, adaptability to external shocks, and institutional commitment. Water governance involves implementing policies and regulations by collaborating with all the stakeholders including policy-makers to beneficiaries. Thus, among climate change impacts and unsustainable practices, the prime focus should be on establishing robust water governance institutions and implementing policies and interventions, to make agriculture resilient and sustainable. Sustainable water management also comes under the purview of the global agenda of Sustainable Development Goals (SDG): 'Transforming our world: the 2030 Agenda for Sustainable Development' (Nations, 2015). The SDGs: No poverty (SDG 1), Zero hunger (SDG 2), Clean water and sanitation (SDG 6), Decent work and economic growth (SDG 8), Sustainable consumption and production (SDG 12), Climate Action (SDG 13), Life on land (SDG 15) and Peace, justice and strong institutions (SDG 16) are directly related to this study. To know if an agricultural system or practice is sustainable, one should consider its economic, social, and environmental dimensions. Hence the following research questions are employed to discuss sustainability issues related to water-stress in the agricultural sector: a) Is water-stress condition limiting the agricultural production and food security of that country? b) Is environmental sustainability ensured in the irrigation practices, irrigation technologies, and land management practices of that country? c) Are water-pricing tools introduced in the country such that they can lead to the financial sustainability of irrigation schemes?

The scope of the present study was to review the sustainability challenges faced in the irrigation systems of Tropical region countries. The Tropical region consists of around 54 countries, which represent a variety of geographic, climatic, governance, and socio-economic conditions. Due to rising population pressure and climate variability, several countries in Asia and Sub-Saharan Africa are projected to be the hotspots for water scarcity, next to North Africa and Middle East countries (Baggio et al., 2021). Seven water-stressed Tropical countries are identified based on a water-stress indicator and analyzed for this study. This study attempts to critically analyze the current irrigation status, irrigation technologies, water policies, and water governance institutions in those water-stressed countries. Thus, the objectives of the study are: 1) to critically review the irrigation status in the identified seven water-stressed Tropical countries, 2) to discuss the pillars of sustainability by highlighting the best practices in those countries, and 3) to propose solutions and recommendations for sustainable water governance. The discussion aims to deliver ground-level and policy-level solutions for stakeholders and policymakers.

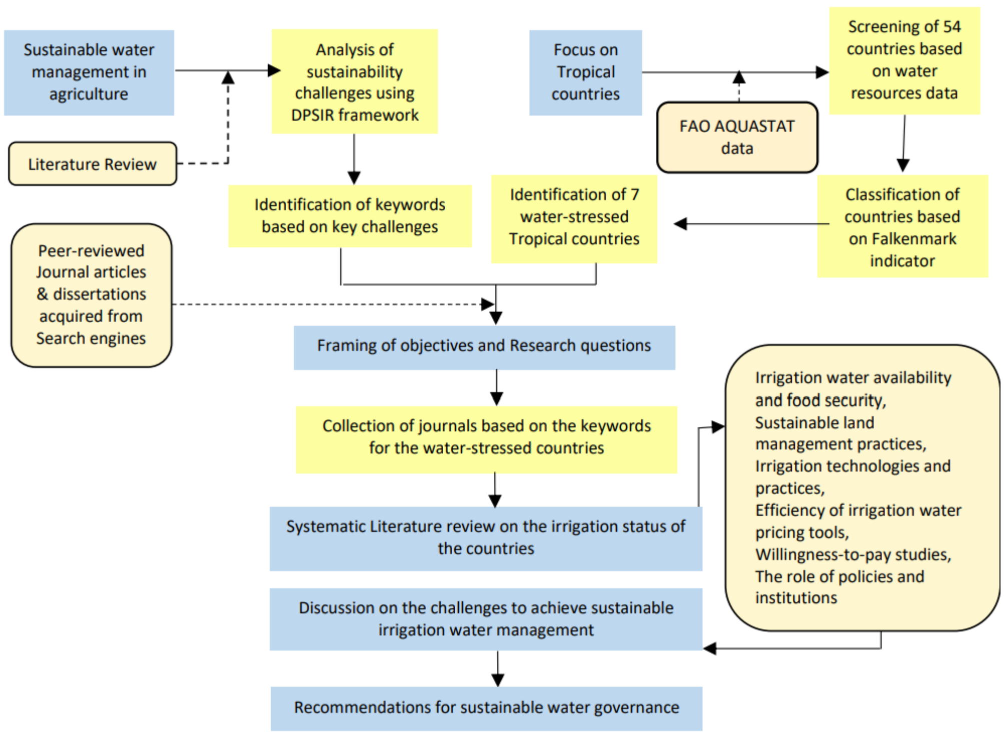

Figure 2. Methodology adopted for systematic literature review.

2. Material and Methods

Figure 2 enumerates the detailed methodology of this study. To analyze the sustainability challenges in irrigation water management, a DPSIR conceptual framework was worked out as illustrated in Figure 3. The driving force-pressure-state-impact-response (DPSIR) framework developed by the European Environment Agency (EEA) is an effective tool to critically analyze the pressure and impacts caused on any natural system due to anthropogenic and climate-driven driving factors (Smeets and Weterings, 1999). The sub-systems that are connected to agriculture were identified, based on the report of the Organisation for Economic Co-operation and Development (OECD) (Parris, 2010): food resources sub-system, water resources, climate system, socio-economic system, ecosystem, and associated cultural recreational value. The driving factors such as climate change, population growth, etc. when interacting with the sub-systems exert pressure on the environment in the form of decreased soil fertility, resource depletion, etc. These result in changes in the state of the environment (as infertile land, change in quality and quantity of available natural resources), which further have socio-economic impacts (like low crop yield, loss of farm income, and decreased livelihood).

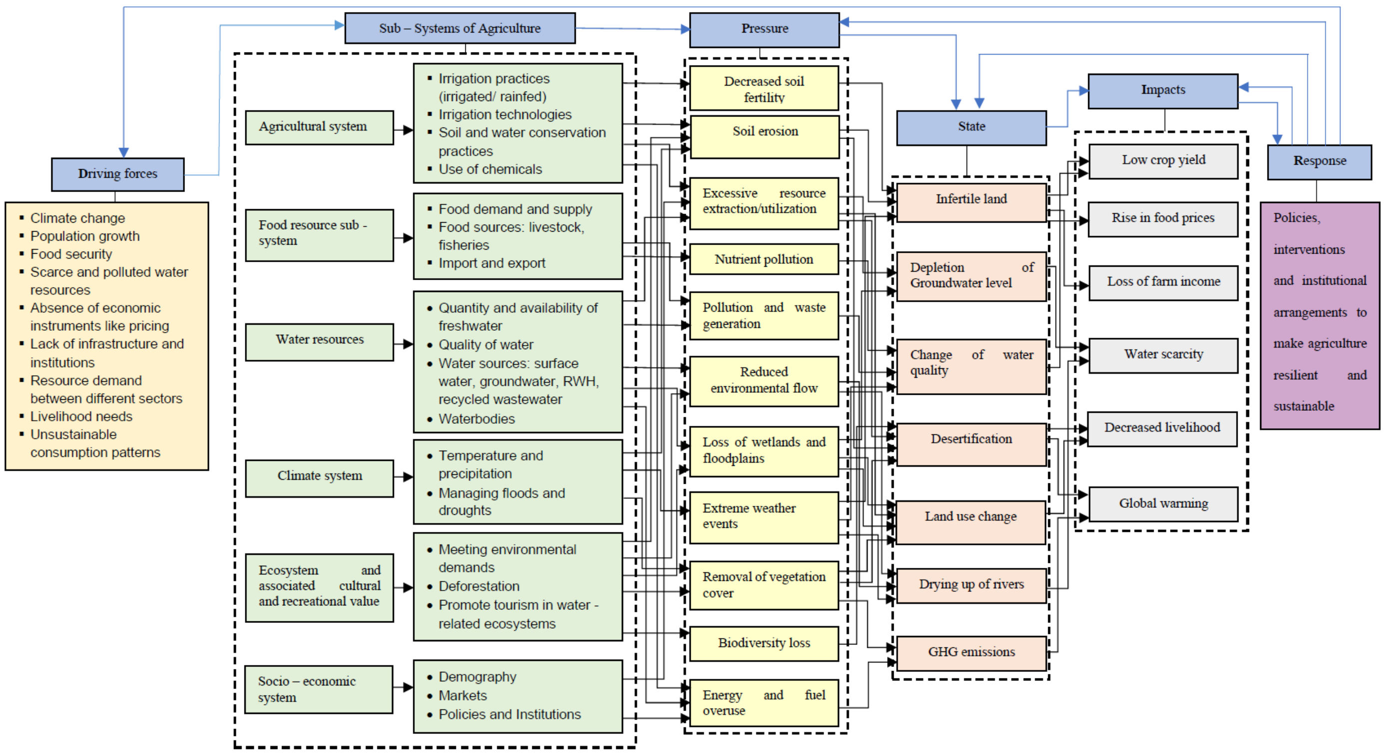

Figure 3. DPSIR Conceptual framework for sustainable water management in agriculture (Source: Illustrated by the authors by adopting the sub-system concept of Parris, 2010; and DPSIR framework of Smeets and Weterings, 1999).

2.1. FAO AQUASTAT Data and Water-Stress Indicator

The Tropical region exists from the Tropic of Cancer (23°N) in the North to the Tropic of Capricorn (23°S) in the South. Due to the wide variability in rainfall and water availability in the Tropical countries, the FAO AQUASTAT country profiles were accessed to get baseline country data for all the Tropical countries. The AQUASTAT database (FAO, 2020), an initiative of the Food and Agricultural Organization (FAO), is a global repository that has around 180 indicators on water resources availability, irrigation, drainage, pressure on water resources, SDG indicators related to water consumption and few factors on environment and health. The AQUASTAT data have been pooled in through extensive country-wise surveys, and data processing and then verified with national authorities before dissemination (Eliasson, 2003).

Falkenmark (2007) defines blue water scarcity as when water in rivers and aquifers becomes scarce and Green water scarcity refers to the depletion of water in the soil which will lead to crop failure. Liu et al. (2017) while reviewing the water-stress indicators, highlight the features of (i) the Falkenmark indicator, (ii) the Water use to Availability Ratio (gives unrealistic low water scarcity values), (iii) Physical and Economic water scarcity-IWMI indicator (complex and less intuitive interpretation) and (iv) Water Poverty Index (comprehensive). Falkenmark indicator is used in this study, as it is widely used because of its simplicity and it indicates the supply side effects. Based on Falkenmark (2007) indicator, the countries for which the per capita water availability was between 1000 to 1700 m^3/year are classified as water-stressed countries, while the countries with less than 1000 m^3/year per capita water availability are classified as water-scarce countries. For the purpose of this study, the total renewable water per capita for each Tropical country was collected from the

AQUASTAT database (FAO, 2020) as listed in Table 1 for the year 2020. The list of identified seven water-stressed countries, their per-capita water availability, area, and population density are listed in Table 2 and the analysis done on other parameters such as Human Development Index (HDI), Gross Domestic Product (GDP), and SDG indicators connected to water-stress are attached in the Supplementary material (Table S1 and Figures S1-S3).

Table 1. List of tropical countries and total renewable water resources per capita for each country (for the year 2020).

S. No.	Country	Total Renewable Water Resources Per Capita (m^3/year)	S. No.	Country	Total Renewable Water Resources Per Capita (m^3/year)
1	Angola	4515.27	28	Maldives	55.5
2	Antigua and Barbuda	531	29	Mali	5925.68
3	Bangladesh	7450.58	30	Mauritania	2451.79
4	Bhutan	101087.6	31	Myanmar	21463.05
5	Cambodia	28476.64	32	Nepal	7214.24
6	Central African Republic	29193.95	33	Nicaragua	24834.88
7	Chad	2782.2	34	Niger	1406.64
8	Colombia	46381.01	35	Nigeria	1388.38
9	Comoros	1379.94	36	Panama	32285.4
10	Costa Rica	22182.45	37	Paraguay	54366.34
11	Cuba	3365.52	38	Peru	57012.26
12	Dominican Republic	2778.32	39	Philippines	4371.19
13	Ecuador	25075.02	40	Republic of the Congo	150776.9
14	El Salvador	4050.13	41	Rwanda	1026.85
15	Ethiopia	1061.21	42	Singapore	102.56
16	Ethiopia	1061.21	43	Somalia	924.92
17	Ghana	1808.65	44	South Sudan	4422.12
18	Ghana	1808.65	45	Sri Lanka	2465.76
19	Guatemala	7139.6	46	Sudan	862.04
20	Guyana	344541.8	47	Tanzania	1611.64
21	Honduras	9305.16	48	Thailand	6283.81
22	India	1384.71	49	Uganda	1313.92
23	Indonesia	7380.35	50	Uganda	1313.92
24	Jamaica	3654.98	51	Uruguay	49572.07
25	Kenya	570.94	52	Venezuela	46595.96
26	Kenya	570.94	53	Vietnam	9082.94
27	Malaysia	17920.04	54	Zambia	5700.62

Source: FAO (2020); Retrieved from https://data.apps.fao.org/aquastat/?lang=en (accessed on 30 November 2023).

Table 2. List of selected water-stressed tropical countries, with their area and population density.

Country	Total Renewable Water Resources Per Capita (m^3/year)	Total Area (1000 ha)	Population (1000 inhabitants)	Population Density (inhabitants/km^2)
Ethiopia	1061.21	1,13,623.95	1,14,963.59	101.18
Niger	1406.64	1,26,700.00	24,206.64	19.11
Nigeria	1388.38	92,377.00	2,06,139.59	223.15
Rwanda	1026.85	2,634.00	12,952.22	491.73
Tanzania	1611.64	94,730.00	59,734.22	63.06
Uganda	1313.92	24,155.00	45,741.01	189.36
India	1384.71	3,28,726.00	13,80,004.39	419.8

Source: FAO (2020); Retrieved from https://data.apps.fao.org/aquastat/?lang=en (accessed on 30 November 2023).

2.2 Methodology Adopted for Systematic Literature Review

Based on the objectives, various peer-reviewed articles from journals and reports were collected for the seven selected countries based on the following keywords: sustainability analysis, sustainability indicators, food security, irrigation water availability, sustainable irrigation water management, irrigation practices, irrigation technologies, economic effects of irrigation technologies, land management practices, efficiency of water pricing tools and analysis of willingness-to-pay studies. About 105 articles were identified based on the keywords from Search engines. After initial screening and filtering of articles due to their less relevance to the scope of the study, 60 articles were included in the qualitative review. While reviewing each literature, the content was subdivided into four sections and elaborated:

irrigation water availability and irrigation status (technologies and practices) in that country, sustainable land management practices, efficiency of water-pricing tools and willingness-to-pay studies, and role of policy reforms. The discussion section was focused on answering the research questions of the study such as the resilience of agriculture to climate variability impacts and on the pillars of sustainability such as the financial sustainability of irrigation systems, the socio-economic condition of farmers, and the role of institutions and threats to environmental sustainability. Based on the discussion findings, recommendations for sustainable water governance have been proposed for policy-level and ground-level implementation.

2.3. Systematic Literature Review of Irrigation Status in Water-Stressed Tropical Countries

Out of the six water-stressed African countries, Niger and Nigeria are located in Western Africa while Ethiopia, Uganda, Rwanda, and Tanzania are situated in the Eastern part of Africa. The status of irrigation in the six water-stressed African countries and India based on a literature survey is presented in detail in this section.

2.3.1. Irrigation Water Availability and Food Security

Water availability for irrigation is crucial to achieve food security. The water-stressed condition affects not just the quantity of food production, but also the quality, varieties, and seasonal availability of food produced. Table 3 explains the challenges in the availability of irrigation water and its associated impacts in the seven countries.

Table 3. Challenges on Irrigation water availability and food security.

Country	Challenges	Impacts	References
Ethiopia	About less than 5% of the irrigable land is irrigated	a long-standing impact on the agricultural communities and also in the food chain	Kassa and Andualem (2020)
	Food insecurity for the past four decades Droughts	-	
Niger	Declining average rainfall Recurring droughts	Low crop production Price rise of food commodities	Soumaila (2021)
Nigeria	Rainfall variability due to geography (Sudano- Sahelian region)	Food insecurity in 49% of urban households	Xie et al. (2017)
	Predominantly rainfed irrigation Prone to droughts and desertification	-	
Rwanda	Excess rainfall for 7 months	Low crop production as its predominantly rain-fed irrigation	Ngango and Seungjee (2021)
	Erratic rainfall pattern	-	
Tanzania	Spatial and temporal variability of rainfall	Less water storage structures	Van Koppen et al. (2007)
	Low level of infrastructure development Increase in rice demand.	Increasing irrigation water demand	Materu et al. (2018)
	Few basins are water-scarce.	-	
Uganda	Drought-hit in 2010 and 2014 Dependent on rain-fed irrigation	Low agricultural production during drought years	Sridharan et al. (2019) Ogwal (2019)
India	Population pressure Spatial variability of rainfall Increase in the number of drought years since 2000	Decreasing freshwater availability Crop damage during dry spells and floods Increasing dependence on groundwater irrigation	Jain et al. (2019) Sikka et al. (2022)
	Groundwater over-exploitation	-	

Promoting irrigation technologies and establishing irrigation schemes are the key elements to increase agricultural productivity in water-stressed countries. Adoption of irrigation depends on various factors including availability of surface water and groundwater, water abstraction devices, irrigation infrastructure, cost of crop production, farm management practices, soil conditions, and financial stability of the government (Ngango and Seungjee, 2021). Table 4 represents in brief the current irrigation practices and technologies followed in the seven water-stressed countries.

Table 4. Irrigation practices and technologies.

Country	Current Irrigation Schemes and Technologies	Remarks	References
Ethiopia	Less than 5% of arable land is irrigated Community-based: small-scale systems (<200 ha) Community-based: Medium-scale (200 to 3000 ha) Commercial: Large-scale systems (>3000ha) The government ratifies the use of cost-effective micro-irrigation technologies. Presence of Small Scale Irrigation Schemes (SSSIs)	Community-based schemes are under WUAs and Irrigation cooperatives Commercial schemes are under the control of State enterprises Treadle pumps, low-pressure drip kits, small diesel pumps, small basins, pits, and runoff-based systems are used. Improvement in land and water productivity through a diversified cropping pattern Increase in crop revenue in rain-fed season too.	Kassa and Andualem (2020) Eshete et al. (2020) Berhe et al. (2022) Kassie (2020)
Niger	Public irrigation and Private irrigation (Farmer-led irrigation)	Water abstraction devices: Treadle pumps (<0.5 ha) and motor/solar pumps (>0.5 ha land)	Soumaila (2021)
Nigeria	Predominantly rain-fed agriculture	Mulching, cover crops, and organic manure are in practice, while other water-smart and nutrient-smart CSA technologies are yet to be adopted.	Xie et al. (2017) Anugwa et al. (2021)
Rwanda	Agriculture is largely subsistence and predominantly rain-fed Smallholder irrigation	Low crop yield Crop failure	Ngango and Seungjee (2021)
Tanzania	System of Rice Intensification (SRI) technique Spate irrigation system	Conserved 35% water when compared to the conventional flooding Consumes water with low opportunity cost Disadvantage: Land quality degradation during flash floods Huge labor costs for temporary weirs and intake structures	Materu et al. (2018) Komakech et al. (2011)
Uganda	Less than 3% of arable land is irrigated. Pressurized drip irrigation is promoted.	Rehabilitation of irrigation structures aids in irrigating during the dry season. Smart drip irrigation systems are in use: valley tank dam, solar power station, water sensors and control unit, and networking infrastructure.	Opio and Mwesigwa (2021)
India	The average irrigation efficiency in Indian irrigated systems is 38% anal irrigation - 23.66% Tank irrigation - 2.52% Groundwater irrigation - 62.82% Micro irrigation - 11%	14.2% of groundwater assessment units are in the "over-exploited" category. Flouride contamination in groundwater over-exploited states of Gujarat and Rajasthan. Micro irrigation has increased irrigation cost savings energy conservation and farmers' income by 42%	Central Ground Water Board (2022) NMMI (2010) Mahajan (2021) Jain et al. (2019) Paria et al. (2021)

2.3.2. Sustainable Land Management Practices

Low productivity of agricultural lands has been witnessed due to the imbalances in both production and population in Ethiopia. Factors such as unreliable rainfall, continuous degradation of land, and increasing population, have led to the conversion of forests into agricultural lands by using rangelands and deforestation (Kassa and Andualem, 2020). Teklay and Ayana (2014) commented that about 33% of the irrigated area in the Awash basin became unfit for cultivation, just after 5 to 8 years of operation due to the salinity of the soil in the agricultural plots. Soil moisture stress during the long dry episodes and excessive siltation problems add up to the agronomic stress of the agrarian soils of Ethiopia (Berhe et al., 2022). As the arid north-eastern region of Uganda experiences a high rate of evapotranspiration, almost twice that of the rate of precipitation, during dry spells the soil moisture becomes critical (Sridharan et al., 2019). Land degradation in Nigeria occurs due to erosion and hydrological causes like flooding and drainage (Oluwadare, 2014).

2.3.3. Efficiency of Water-Pricing Tools

Irrigation projects require large investments and funding. To ensure the long-term sustainability of the schemes, demand management strategies must be explored and implemented. Economic instruments such as water pricing and water markets can serve as cost-recovery mechanisms. When water users are encouraged to pay for the operation and maintenance of irrigation infrastructure, they also develop a sense of ownership and conservation towards the scarce water resource. Table 5 displays the pricing system prevalent in the water-stressed countries and their efficiency.

Table 5. Water-pricing tools used and their efficiency.

Country	Water-Pricing Tools	Efficiency of Tools and Outcomes	References
Ethiopia	Volumetric pricing mechanism (Functional in Awash basin)	The charges are quite low to signal the users to improve their crop water productivity	Teklay and Ayana (2014)
	Community by-laws (in other basins)	Followed by WUAs for fee collection	Ayana et al. (2015)
Niger	Three strategies of pricing: Price Structure, Price level & Sanction system	Prices may be paid in cash, labor, percentage, or fixed value of crop production and/or any combination of these goods.	Schrecongost (2005)
Nigeria	Low-cost Recovery	Govt. bodies need to subsidies irrigation projects and shift to privatization.	Adekalu et al. (2003)
Rwanda	Planned to implement cost-reflective tariffs	Increasing fee collection and recovery costs for rehabilitation and maintenance	Rwanda IMP (2020)
Tanzania	For cost recovery, a new administrative water rights and fee payment system was implemented.	Was feasible to recover the costs from large-scale private water users only, rather than the poor small-scale water users	Van Koppen et al. (2007)
	Economic water-users fee was introduced in 1994	-	
Uganda	The Water Act of Uganda	Water is free only for local residents for domestic and subsistence garden irrigation, while commercial farmers are charged. Water is a community property and private ownership of water is not recognized.	Ogwal (2019)
	African customary law	-	
India	Crop-specific water rates are in practice.	Pricing varies with every State (province). Water prices have not been revised for the past four decades. Volumetric water pricing (recommended in all the States by National water policy)	Central Water Commission (2017) NWP (2012) Clency (2000) Mahajan (2021)
	Enactment of Farmers' Management of Irrigation Systems Act in 18 States out of 28 States	Revision of irrigation water tax and establishment of a structured collection mechanism.	Manasi et al. (2009)

2.3.4. Willingness-to-Pay Studies

Regulating consumption through a pricing mechanism is a demand management tool in water resources. Willingness-to-pay, a pricing tool, aids in the efficient allocation of water resources among the users and generates revenue for the institutional setups by the Government. This financial assistance will be further used for the operation and maintenance works of the irrigation infrastructures by the respective institutional setups. In a willingness-to-pay (WTP) survey performed in the Gumara Irrigation project, about 98.26% of households were willing to pay a mean WTP amount of 926.7 ETB (ETB= Ethiopian Birr; 1 ETB= 0.018 US$) per month (Getnet et al., 2022). In Tanzania, irrigation was privatized after the closure of the irrigation management governmental agency in 1996. In a willingness-to-pay survey, Tanzanian farmers were willing to pay an average of 45,000 TZS (Tanzanian Shilling, where 1 TZS= 0.00040 US$) per 0.405 hectares per year for the O&M of irrigation, if they were provided access to credit and extension services (Ngaiza, 2019). Bumesse SSIS in Uganda showed negative Net Present Value for all the crops grown (tomato, cabbage, green pepper, and watermelon), meaning that the overall production system must be revised to contribute to food security, investments, and household incomes. In a WTP survey carried out by Anugwa et al. (2021) among Nigerian farmers on adopting climate-smart agricultural technologies, farmers showed their preference to pay $115.63 annually for CSA which included $31.02 for water-smart technologies.

2.3.5. Role of Policy Reforms

In water-stressed countries, policy reforms and institutional arrangements ought to play a crucial role in sustainable water management in agriculture. All levels of farmers should be involved in the decision-making process to manage the water resources sustainably. Community-driven interventions, capacity-building programs, development policies, and schemes should be framed by the policymakers, in view of improving the socio-economic status of the farmers by increasing productivity, effective land management, access to technology and innovation, and access to market and finance. Table 6 outlines a few policy reforms undertaken in the countries and their outcomes.

Table 6. Policy reforms and their outcomes.

Country	Policy Reform	Outcomes	References
Ethiopia	Growth and Transformation Plan (GTP) –I of the Ethiopian government GTP- II	Prioritised expansion of small-holder irrigation Focused on soil fertility management and to develop farmers' skills	Getnet et al. (2022)
Niger	National Sub-Sector Strategy for Irrigation Development	Framing of national development strategies includes the National Food Security Strategy.	Schrecongost (2005)
Nigeria	The Agricultural Transformation Agenda" of the Nigerian Government Policy ban on importation of agricultural produces	Policy shift from developing large-scale dam-based irrigation schemes to establishing SSISs from the 1980s SSIs include the use of low-cost and simple technology equipment (pulley bucket, small reservoirs, and motor pumps) To empower the local farmers to produce their crops	Xie et al. (2017) Adelodun and Choi (2018)
Rwanda	Strategic Plan for Agricultural Transformation (SPAT)	This Policy guides national agricultural policies in Rwanda to increase land under irrigation	Ngango and Seungjee (2021)
Tanzania	Formation of Water Users' Associations (By collecting registration fees and economic water users' fees)	Development of smallholder irrigation was encouraged to collectively obtain a 'water right'	Van Koppen et al. (2007)
Uganda	The Vision 2040 of the Ministry of Agriculture, Animal and Fisheries of Uganda (MAAIF Uganda)	The goal is to 'commercialize agriculture' within 30 years, by adopting water-efficient technologies (like drip irrigation) To achieve maximum production, efficiency, and long-term environmental sustainability and social and economic benefits for Ugandans from water.	Ogwal (2019)
India	Central government schemes on micro-irrigation	The centrally sponsored scheme on micro-irrigation (2006), the National Mission on Micro-irrigation (2010), the National Mission on Sustainable Agriculture (2014), and Prime Minister Krishi Sinchayee Yojana (2015).	Mahajan (2021) Jain et al. (2019)

3. Results and Discussion

3.1. Resilience of Agriculture to Climate Variability Impacts

With the global food demand projected to increase by 50% in 2050, it must be discussed whether water-stressed condition limits the sustainable agricultural production of the countries. Many researchers have studied the ways to improve the resilience of agriculture to climate variability impacts in selected Tropical countries (Nkonya et al., 2015; Olayide et al.; 2016; Oluwadare; 2014; Sikka et al., 2022; Sridharan et al., 2019; Eshete et al., 2020; Abou Zaki et al., 2018). The prevalent impacts observed in the studies were crop diseases, low soil fertility, soil moisture deficit, nature-related factors, over-dependence on rain-fed irrigation, and socio-economic factors. African farmers are left only with two choices: either to cope with alternate strategies for climate adaptation or to switch and settle for another livelihood. The studies indicated that the water-use efficiency of irrigation systems, planned irrigation scheduling, and employing sustainable farming practices strengthen the resilient capacity of agricultural systems and help sustain water and crop productivity. In recent studies, the usage of organic fertilizers has contributed to increased yield (Marasini et al., 2024), and plant-growth-promoting bacteria as a sustainable agriculture practice have improved soil fertility thereby reducing environmental stress on soils (Kumari et al., 2023).

To overcome water stress and combat drought severity, agricultural water management practices and harvesting rainwater should be encouraged. Developing more cultivable land under irrigation can reduce climate-induced risks. Implementing case-specific and location-specific 'climate-smart agriculture' (CSA) techniques can reduce the agricultural production risks caused by climate change. Farming communities should opt for alternate irrigation sources and alternate practices like agroforestry as drought adaptation technologies to overcome climate shocks. Moreover, access to information on weather and climate-smart techniques enhances the farmers' resilience to climate variability, improves their farming skills, and in turn leads to a better livelihood (Ajwang et al., 2024).

3.1.1. Best Practices

Taungya farming (landless farmers cultivating their annual crops in the reserve forests) is supported by the Nigerian government to develop crop production and sustenance of indigenous forest species simultaneously (Oluwadare, 2014). In 121 climate-vulnerable districts in India, the farmers arrived at smart practices to improve resilience, through a participatory approach in the project of the National Initiative on Climate Resilient Agriculture (Sikka et al., 2022). In Central India, rainwater harvesting and Managed Aquifer Recharge (MAR) were adopted in drought-prone watersheds (Sikka et al., 2022). It was observed to raise the groundwater level by 2 to 5 meters.

3.2. Financial Sustainability of Irrigation Schemes

Financial and technological investment in irrigation is a dire necessity to make agricultural production sustainable and thereby ameliorate food security. Cost recovery measures ensure that the present and future water demands are met within the limits of resource availability (Ngene et al., 2021). According to Parris (2010), sustainable cost recovery means finding the right balance between tariffs, taxes, and transfers. The lack of returns, and technological and institutional arrangements in SSA, resulted in the decline of large public infrastructure projects in SSA. Van Koppen et al. (2007) observed the insufficiency of objectivity and transparency in the enforcement of cost-recovery. In addition, non-mechanized irrigation tools, dysfunctional dams, funding constraints, low project efficiency, lack of coordination between water resources and agriculture department, and lack of knowledge among farmers about irrigation techniques are the major challenges for financial sustainability in irrigation. The sustainability of irrigation projects is threatened by inadequate funding and less participation from the private sector. The economic performance of the irrigation projects will be enhanced by improving agricultural productivity, cultivation of profitable crops with market access, optimization of cost with well-specified pricing objectives, cost recovery from large-scale private users, and intangible values of irrigation water. Out-sourcing the technological capacity of private sectors can also maintain the financial sustainability of irrigation schemes. Investing in improving the marketing system and road infrastructures can aid in more farmers being included in the irrigation system. The studies proved that the contribution of funding agencies and NGOs aid the SSISs by providing irrigation equipment. Table 7 outlines the challenges related to cost-recovery mechanisms in Ethiopia and India, followed by case studies of successful financial models in a few countries.

Table 7. Challenges to cost-recovery mechanisms and case studies of successful financial models.

Country	Challenges Related to Cost-Recovery Mechanisms	Proposed Solutions	Case Studies of Successful Financial Models	References
Ethiopia	Ambiguity of roles and responsibilities at different levels (Region and basin offices)	Focus on decentralization by explaining clear roles and responsibilities	Ethiopia has a well-formulated Policy and a well-structured organizational setup to implement water pricing. IWUAs are involved in implementing the water pricing policy.	Hagos et al (2022) Otoo et al (2018) IWMI (2021)
	Revenue collection reverted to centralization.	Provide access to loans for farmers to set small-scale farmer-led groundwater irrigation	Small-scale Solar irrigation pumps:	
	Limited access for farmers to pump water High pump prices for expanding groundwater irrigation Lack of loans for purchasing pumps	Reduce the cost of unsuccessful borehole drilling to overcome high drilling costs and uncertainty in hitting the groundwater.	As fuel-powered pumps can increase CO_2 emissions, the government of Ethiopia is expanding Solar-powered irrigation pumps in small-scale irrigation. Farmers are exempted from paying VAT and import taxes.	
India	Non-implementation of volumetric water pricing	Revising the Water Policy by elaborating on volumetric pricing.	A range of water-pricing mechanisms exist in different Indian States (Area-based pricing and Crop-based pricing).	Malik et al (2014) Palanisami et al (2015)
	Poor compliance with revenue collection	Ensure the formation of a Water Regulatory Authority in every State for revenue collection and maintenance of irrigation systems.	In India, micro-irrigation subsidy is provided for each category of farmers. The government of India has also created the Micro Irrigation Fund (MIF) with the National Bank for Agriculture and Rural Development (NABARD) to facilitate the States to expand micro-irrigation coverage.	
	Lack of willingness to pay due to inefficient water allocation Subsidized water charges Poor recovery rates Non-allocation of finances for maintenance	Need for a sustained political commitment to enforce water pricing		

3.2.1. Case Studies of Successful Financial Models

Enabling poor smallholder farmers to acquire irrigation equipment requires adopting selective financial models through a well-established institutional arrangement. In Sub-Saharan Africa, micro-credit and micro-finance services provide 'short-term seasonal credits' to farmers (Merrey and Lefore, 2018). It serves as a poverty reduction strategy and also helps smallholder farmers to gain access to small-scale irrigation equipment. The locally owned microfinance institutions (MFIs) provide credit to farmers and it has impacted increasing food security and the capacity of women's income generation. In a study carried out in three states of Ethiopia, access to micro-credit was found to significantly influence farmers' adoption of irrigation technology (Hagos et al., 2022).

The solar irrigation project in Rwanda has incorporated a few financial models like leasing, mobile layaway, and rent-to-own systems (Merrey and Lefore, 2018). These models are successful as it is 'farmer-friendly financing'. These models are instrumental in attracting many smallholders to cost-saving and energy-efficient schemes and technologies. The solar irrigation scheme in the Bihar state of India follows the own-operate-rent model for using the portable solar array and pump trolley (Merrey and Lefore, 2018). Nearly 350 farmers benefitted from it and 30% of them were women.

3.3. Socio-economic Challenges of Farmers and Institutional Sustainability

The success of irrigation schemes requires cooperation between farmers' associations and governance institutions. The challenges faced by farmers are lack of appropriate training, research, capital, low development of social and institutional aspects, limited participation of the community and weak local institutions, public acquisition of water rights, lack of institutional capacity, unstable land tenure, high population density, and water scarcity (dry seasons). The governance institutions must provide extension policies and technical assistance to the affected communities (Ogunniyi et al., 2018). Organizing capacity-building programs to empower the farmers, extension workers, and development agencies, leveling up irrigation technologies to maximize the yield, participation of stakeholders, mainstreaming gender, and developing multipurpose irrigation projects are some of the actions that can be taken up by the governments. More examples of training programs and community-based interventions are explained in Table 8.

Table 8. Training programs, institutional reforms, and successful community-based interventions.

Country	Training Programmes and Institutional Reforms	Case Studies of Successful Community-based Interventions	References
Ethiopia	Rural Capacity Building Project (RCBP) an agricultural extension service provided access to information on increased cash–crop farming in Ethiopia	Participation of farmers in the Small-Scale Irrigation (SSI) scheme increased agricultural production as well as livelihood capital assets in the Awash sub-basin, Ethiopia.	Maru et al. (2023) Buehren (2019)
Niger	The yield of trained farmers on the use of information of Climate Services (CS) is found to be 17% higher than the non-trained farmers in the regions of Dosso and Tillabéri in Niger.	The establishment of Sustainable Irrigation Water User Associations (AUEI) in Niger improved water management and recovered more amount of fees.	Bacci et al. (2023) Abdoulkarimou and Mahamadou (2024)
Rwanda	Through the 'Umuganda' development policy Government of Rwanda (GoR) farmers were being trained by experts about the role of irrigation and water-saving techniques.	Concern Worldwide Rwanda Livelihoods Programme by the Government of Rwanda (GoR) works through local partner organizations where the small land-holding farmers were brought to work together and as a result, all the participants' crop productivity has increased.	Theobald and El-Sayed (2019) Willoughby and Forsythe (2012)
Tanzania	Modified System of Rice Intensification (MSRI) rice production training to the farmers of Kilombero District, Moro-goro region of Tanzania resulted in a significant increase in rice profit of 191.5 USD per hectare where MSRI was adopted.		Nakano et al. (2018)
Uganda	Through the Lowland Rice Training Project in Uganda, the farmers were trained for the adoption of improved cultivation practices, which enhanced lowland rice profits.	The Plan for Modernization of Agriculture (PMA) by the Government of Uganda has a significant impact on the socio-economic status of small land-holding farmers.	Wamala et al. (2017) Kijima et al. (2012)
India	Under the Rural Agricultural Work Experience Programme (RAWEP) (capacity building program), the awareness of the application of bioagents increased to 30% resulting in greater yield and reduced usage of pesticides in the Hassan District of Karnataka.	The establishment of WUA resulted in a 41% increase in employment and a 75% increase in income for the members of the WUA in the Puri District, Odisha.	Mishra (2023) Shankara et al. (2023)

3.4 Threats to Environmental Sustainability and Adaptive Measures

Environmental sustainability can be defined as that condition that allows society to meet its needs within the carrying capacity of nature and the ecosystem in such a way that its regenerative capacity and biological diversity are not endangered (Vos, 2007). It was observed in this study that unsustainable agricultural production practices have imparted environmental pressure in the form of continuous degradation of land (Oluwadare, 2014), due to the conversion of forests into agricultural lands (Kassa and Andualem, 2020), salinity of soil in agricultural fields, thereby resulting in low production (Teklay and Ayana, 2014), soil moisture stress due to higher rates of evapotranspiration (Sridharan et al., 2019) and wastage of water due to low irrigation efficiency (Jain et al., 2019).

3.4.1. Agricultural Intensification and Groundwater Exploitation: Indian Scenario

Many studies (Jain et al., 2019; Paria et al., 2021; Sikka et al., 2022) arrived at a grounding truth that the shift from surface irrigation to groundwater irrigation in India was attributed primarily to of green revolution and other causes such as supply of subsidized inputs to farmers, increasing gap between irrigation potential created and utilized due to the delayed development of on-farm development works, lack of legal and institutional complexities and non-metering of electricity consumption. Food security was prioritized through the Green Revolution while sustainable resource use was ignored. Sikka et al. (2022) present a worst-case scenario stating that if the present groundwater depletion trend prolongs, it will lead to food insecurity as the cropping intensity might reduce by overall 20% in India and in groundwater-depleted regions up to 68%. Paria et al. (2021) expressed that this trend of excessive groundwater usage and decreasing cultivable command areas (CCA) under surface irrigation may raise an alarm for a hydro-ecological imbalance in the near future. In order to make agricultural intensification sustainable and to bring back groundwater sustainability, crop diversification schemes, creating alternate irrigation sources like rainwater harvesting, and accentuating cultivating less-water intensive crops must be brought as interventions.

3.4.2. Adaptive Measures to Achieve Environmental Sustainability

Improving the water-use efficiency of existing irrigation schemes by smart irrigation scheduling, deficit irrigation, and following new agronomic practices like laser-guided land leveling can improve the water productivity of the irrigation systems. Adopting climate-resilient agricultural practices in water and land management which majorly reduce greenhouse gases (GHG) emissions, cultivating water stress-tolerant crops such as orchids (pomegranates) during dry seasons, adopting new methods like direct-seeded rice technique which have a low global warming potential can reduce the global climate change impacts and improve the resilience of the farming communities.

The organic content in soil and soil moisture retention can be improved by adopting conservation agriculture practices with reduced tillage and soil mulching where water-intensive rice and wheat irrigation occurs. Crop diversification can be advanced through small-scale irrigation schemes (SSISs). Spate irrigation can be promoted as an alternate irrigation source in arid and semi-arid regions. The governments must ratify the use of low-cost micro-irrigation systems bring in policies that de-subsidize free electricity and introduce slab systems for groundwater irrigation by working out an optimal crop plan which focuses on irrigating less-water-intensive crops in groundwater-depleted regions.

3.4.3. Best Practices

Planned and effective management of surface and groundwater can also be a demand management effort to improve water-use efficiency through conjunctive use. During the monsoon months in the Gangetic basin, India, a study was piloted to erect a Managed Aquifer Recharge (MAR) infrastructure for the "Underground transfer of floods for irrigation" (UTFI). This aided in recharging the depleted aquifers and also reduced the flood risk of that basin.

3.5. Way Forward for Sustainable Water Governance

Water users, stakeholders, and decision-makers working coherently in the process of policy formulation and institutional interventions, towards water sustainability and management can be referred to as water governance (Rogers and Hall, 2003). The Organisation for Economic Cooperation and Development (OECD) formulated 12 principles on which a water governance system can be built (OECD, 2015). The three main dimensions of OECD's 12 principles are Effectiveness, Efficiency, Trust, and Engagement. Based on the review findings, the following recommendations are made based on these 12 principles and represented in Figure 4.

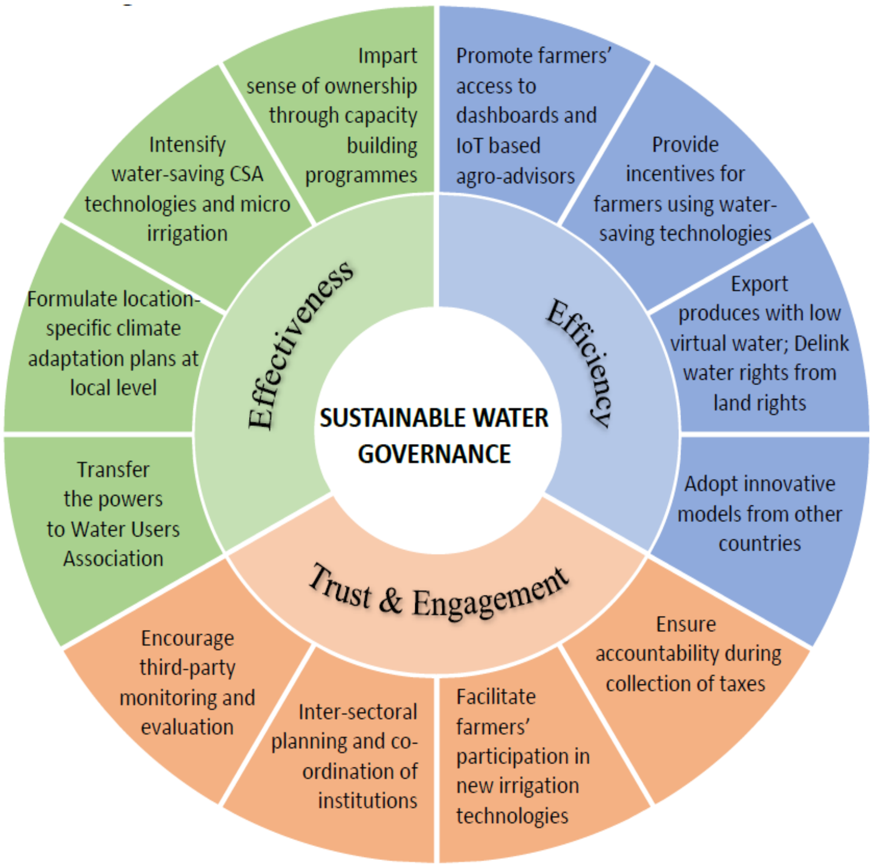

Figure 4. Recommendations for sustainable water governance (Source: Illustrated by the authors based on OECD, 2015)

3.5.1. Effectiveness

Improve the capacity of small-scale farmers through capacity-building programs. To bridge the gap between irrigation potential created and utilized, adopt area-specific solutions incorporating Agricultural Water Management (AWM) interventions. Adopt efficient technologies such as water-saving CSA technologies, micro irrigation, and alternate sources of irrigation.

3.5.2. Efficiency

Micro-irrigation must be boosted at a large level, along with working out the optimal crop plan; that is, to manage water by shifting more water-intensive crops to water-rich areas. The economic efficiency principle should be enforced to make water users pay a price that includes both direct and indirect costs of water usage. Elimination of subsidies that encourage further water extraction. Equity principles and water conservation are to be upheld while assigning water prices. Reconsidering trade policies in order to balance virtual water trade: exporting vegetables and fruits that have low virtual water during their production. There is a need to frame policies and interventions that also focus on the efficiency of the irrigation system and the long-term sustainability of the natural resource base. Delinking the water rights from land rights from private land owners to minimize water over-extraction and also sensitize the users towards sustainable extraction and recharging.

3.5.3. Trust and Engagement

Promoting social inclusiveness through the participation of farmers and the effective functioning of WUAs are keys to establishing a robust water governance system. Water resilience must be recognized as the key to agricultural resilience; Adaptation to climate change must be done at the local level. While intensifying agriculture, a sustainable and inclusive approach is required to rightly balance environmental needs and societal needs. Advancing and encouraging farmers' active participation in new water-saving technologies by providing incentives. Ensuring accountability and transparency during the collection and handling of water taxes. Inter-sectoral planning and confluence of institutions must be initiated in irrigation reforms. For effective evaluation of irrigation projects, encourage third-party monitoring and evaluation.

4. Conclusion

Sustainability studies warrant us to think globally and act locally. An attempt was made in this review to analyze the nexus that exists between water and land management, water and food production systems, water and climatic systems, and water and socio-economic structures. The water-stressed Tropical countries that are vulnerable to impacts were chosen for the study. The discussion and best practices brought out important findings such as: promoting the implementation of climate-smart agricultural practices, shifting to water-saving technologies, enforcing policies and regulations, and empowering the WUAs can ensure environmental, financial, and institutional sustainability in the irrigation systems. It is recommended from this study to focus on formulating location-specific climate adaptation plans and to provide access to farmers to IoT-based systems so that farmers can equip themselves for future climate shocks and livelihood vulnerabilities. It is inferred from the study that Policy reform that was successful in a country may be a constraint in another country. Apart from geographical conditions, the success of public policies depends on the population, poverty index, educational status, human development index, and political commitment of that country. As an action agenda, IoT-based access to information should be enhanced so that farmers will be made aware of climate-resilient crops, drought-tolerant crops, etc. Policymakers must ensure that farmers receive proper training through capacity building. If there is a sustainable water users association (WUA), membership should be provided to all, so that the farmers receive economic returns. Pricing of irrigation water can imbibe a sense of responsibility among farmers and will encourage conservation. Further research could be carried out based on other water-stress indicators and the performance evaluation of irrigation schemes by incorporating all stakeholders. In order to achieve sustainable water governance, collective action from all stakeholders is required. Governance systems with a bottom-up approach, transparency, and accountability can establish sustainability in irrigation water management in Tropical countries.

Author Contributions: Conceptualization: Tryphena Magdalene J., Carolin Arul; Data curation: Tryphena Magdalene J., Melba Respina B.; Investigation & Resources: Tryphena Magdalene J., Melba Respina B., Vaishnudurga Parthipan; Methodology: Tryphena Magdalene J., Carolin Arul, Melba Respina B.; Supervision & Validation: Carolin Arul; Visualization: Melba Respina B., Tryphena Magdalene J.; Writing – original draft: Tryphena Magdalene J.; Writing – review & editing: Tryphena Magdalene J., Carolin Arul, Melba Respina B., Vaishnudurga Parthipan. All authors have read and agreed to the published version of the manuscript.

Funding: The first author of this manuscript (Tryphena Magdalene J.) is receiving Anna Research Fellowship funded by Anna University, Chennai for Ph.D. research work.

Acknowledgment: The authors are grateful to the institution Anna University for funding the research work through the Anna Research Fellowship. The authors wish to thank the anonymous reviewers for the expected constructive suggestions and all the members of the editorial team. The authors would like to thank the co-research scholars who supported this study.

Conflicts of Interest: All the authors declare that we do not have any conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: Data will be made available on request to the corresponding author. The water availability and irrigation data used in this study were open-source data available with the FAO AQUASTAT website (https://data.apps.fao.org/aquastat/?lang=en).

Supplementary Information Availability: Online version of this article contains supplementary material available at: https://doi.org/10.xxxx .

References

Abdoulkarimou, S., & Mahamadou, I. (2024). Reform of the Irrigation Sector and Creation of Functional and Sustainable Irrigation Water Users Associations (AUEI) in Niger: Capitalization of the Experience of the Konni AHA. *Agricultural Sciences*, 15, 209-229, 10.4236/as.2024.152012.

Abou Zaki, N., Torabi Haghighi, A., Rossi, P. M., Xenarios, S., & Kløve, B. (2018). An index-based approach to assess the water availability for irrigated agriculture in sub-Saharan Africa. *Water*, 10(7), 896, https://doi.org/10.3390/w10070896

Adekalu, K. O., & Ogunjimi, L. A. O. (2003). Cost recovery strategy for large-scale irrigation projects in Nigeria. *Technovation*, 23(1), 77-83, https://doi.org/10.1016/S0166-4972(01)00057-8

Adelodun, B., & Choi, K.S. (2018). A review of the evaluation of irrigation practice in Nigeria: Past, present and future prospects. *African Journal of Agricultural Research,* 13(40), 2087-2097, https://doi.org/10.5897/AJAR2018.13403

Ajwang, S., Owoche, P., & Mutonyi, J. (2024). Access and Use of Information for Enhanced Adoption of Climate Smart Agricultural Practices among Smallholder Farmers in Lake Victoria Basin, Kenya. *AgroEnvironmental Sustainability*, 2(2), 62-73, https://doi.org/10.59983/s2024020201

Anugwa, I.Q., Onwubuya, E.A., Chah, J.M., Abonyi, C.C., & Nduka, E.K. (2022). Farmers' preferences and willingness to pay for climate-smart agricultural technologies on rice production in Nigeria. *Climate Policy,* 22(1), 112-131, https://doi.org/10.1080/14693062.2021.1953435

Ayana, M., Teklay, G., Abate, M., Eshetu, F., & Mada, M. (2015). Irrigation water pricing in Awash River Basin of Ethiopia: Evaluation of its impact on scheme-level irrigation performances and willingness to pay. *African Journal of Agricultural Research*, 10(6), 554-565, https://doi.org/10.5897/AJAR2014.9381

Bacci, M., Idrissa, O. A., Zini, C., Burrone, S., Sitta, A. A., & Tarchiani, V. (2023). Effectiveness of agrometeorological services for smallholder farmers: the case study in the regions of Dosso and Tillabéri in Niger. *Climate Services*, 30, 100360, https://doi.org/10.1016/j.cliser.2023.100360

Baggio, G., Qadir, M., & Smakhtin, V. (2021). Freshwater availability status across countries for human and ecosystem needs. *Science of the Total Environment*, 792, 148230, https://doi.org/10.1016/j.scitotenv.2021.148230

Berhe, G. T., Baartman, J. E., Veldwisch, G. J., Grum, B., & Ritsema, C. J. (2022). Irrigation development and management practices in Ethiopia: A systematic review on existing problems, sustainability issues and future directions. *Agricultural Water Management*, 274, 107959, https://doi.org/10.1016/j.agwat.2022.107959

Borsato, E., Rosa, L., Marinello, F., Tarolli, P., & D'Odorico, P. (2020). Weak and strong sustainability of irrigation: A framework for irrigation practices under limited water availability. *Frontiers in Sustainable Food Systems*, 4, 17, https://doi.org/10.3389/fsufs.2020.00017

Bruinsma, J. (2003). World agriculture: Towards 2015/30, an FAO perspective. London, Earthscan and Rome, FAO, Available online: https://www.fao.org/4/y3557e/y3557e.pdf (accessed on 4 December 2023).

Brundtland, G. H. (1987). Brundtland report: Our Common Future. Report of the World Commission on Environment and Development. Norway, Available online: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf (accessed on 15 January 2024).

Buehren, N., Goldstein, M., Molina, E., & Vaillant, J. (2019). The impact of strengthening agricultural extension services on women farmers: Evidence from Ethiopia. *Agricultural Economics*, 50(4), 407-419, https://doi.org/10.1111/agec.12499

Central Ground Water Board (2022). National compilation on Dynamic groundwater resources of India, 2022. Report: Central Groundwater Board, Faridabad. Available online: https://static.pib.gov.in/WriteReadData/userfiles/file/GWRA2022(1)HIDO.pdf (accessed on 20 January 2024).

Central Water Commission (2017). Pricing of water in Public system in India. Central Water Commission, Water planning and projects wing, Government of India, Available online: https://cwc.gov.in/sites/default/files/Pricing%20of%20Water%20in%20Public%20System%20in%20India%202017.pdf (accessed on 20 January 2024).

Clency, C. (2000). A critical appraisal of Irrigation cess laws in Tamilnadu. M.E. Thesis: Department of Civil Engineering, Anna University. Centre for Water Resources Library.

Economic Survey (2018). Economic Survey 2017-18 (Vol. 2). Government of India. Available online: https://www.indiabudget.gov.in/budget2018-2019/economicsurvey2017-2018/index.html (accessed on 13 December 2024).

Eliasson, Å., Faurès, J. M., Frenken, K., & Hoogeveen, J. (2003). AQUASTAT–Getting to grips with water information for agriculture. Land and Water Development Division FAO, Rome, Italy. Available online: https://openknowledge.fao.org/server/api/core/bitstreams/e87f25fb-9f67-46e9-a41e-de5092444e2e/content (accessed on 20 January 2024).

Eshete, D. G., Sinshaw, B. G., & Legese, K. G. (2020). Critical review on improving irrigation water use efficiency: Advances, challenges, and opportunities in the Ethiopia context. *Water-Energy Nexus*, 3, 143-154, https://doi.org/10.1016/j.wen.2020.09.001

Falkenmark, M., Berntell, A., Jägerskog, A., Lundqvist, J., Matz, M., & Tropp, H., (2007). On the verge of a new water scarcity: a call for good governance and human ingenuity (pp. 1-19). Stockholm, Sweden: Stockholm International Water Institute (SIWI). Available online: https://siwi.org/publications/on-the-verge-of-a-new-water-scarcity/ (accessed on 20 January 2024).

FAO (2017). Water for Sustainable Food and Agriculture, Food and Agricultural Organisation. Available online: https://www.fao.org/sustainability/en/ (accessed on 20 January 2024).

FAO (2020). FAO AQUASTAT database. Food and Agriculture Organisation, Available online: https://data.apps.fao.org/aquastat/?lang=en (accessed on 20 January 2024).

Getnet, A., Tassie, K., & Ayele, Z. B. (2022). Estimating smallholder farmers' willingness to pay for sustainable irrigation water use in north western Ethiopia: A contingent valuation method study in Gumara Irrigation Project. *Advances in Agriculture*, 2022, https://doi.org/10.1155/2022/6415437

Hagos, F., Ahmed, J., Haileslassie, A., & Seid, A. (2022). Operationalizing irrigation water charges in sub-Saharan Africa: a case study from the Central Rift Valley, Ethiopia. *Water Policy*, 24(6),1014-1033, https://doi.org/10.2166/wp.2022.034

IWMI (2021). Prices, loans or ambiguity? Factors influencing groundwater irrigation adoption in Ethiopia. Colombo, Sri Lanka: International Water Management Institute (IWMI). *IWMI Water Policy Brief* 42, https://doi.org/10.5337/2021.225

Jain, R., Kishore, P., & Singh, D. K. (2019). Irrigation in India: Status, challenges and options. *Journal of Soil and Water Conservation*, 18(4), 354-363, https://doi.org/10.5958/2455-7145.2019.00050.X

Kassa, M., & Andualem, T. G. (2020). Review of irrigation practice in Ethiopia, lessons from Israel. *Irrig. Drain. Syst. Eng,* 9(1).

Kassie, A. E. (2020). Challenges and opportunities of irrigation practices in Ethiopia: a review. *Journal of Engineering Research and Reports*, 9(3), 1-12.

Kijima, Y., Ito, Y., & Otsuka, K. (2012). Assessing the impact of training on lowland rice productivity in an African setting: Evidence from Uganda. *World Development*, 40(8), 1610-1618. https://doi.org/10.1016/j.worlddev.2012.04.008

Komakech, H. C., Mul, M. L., van der Zaag, P., & Rwehumbiza, F. B. (2011). Water allocation and management in an emerging spate irrigation system in Makanya catchment, Tanzania. *Agricultural water management*, 98(11), 1719-1726. https://doi.org/10.1016/j.agwat.2010.07.017

Kumari, E., Kumari, S., Das, S. S., Mahapatra, M., & Sahoo, J. P. (2023). Plant Growth-Promoting Bacteria (PGPB) for Sustainable Agriculture: Current Prospective and Future Challenges. *AgroEnvironmental Sustainability,* 1(3), 274-285. https://doi.org/10.59983/s2023010309

Liu, J., Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., & Oki, T. (2017). Water scarcity assessments in the past, present, and future. *Earth's Future*, 5(6), 545-559, https://doi.org/10.1002/2016EF000518

Mahajan, A. (2021). Cost recovery dynamics of water pricing for irrigation in India: Issues and future implications. *Asian Journal of Management and Commerce*, 2(2), 112-120.

Malik, R. P., Prathapar, S. A., & Marwah, M. (2014). Revitalizing canal irrigation: Towards improving cost recovery (Vol. 160). IWMI Publishing, Available online: https://www.iwmi.org/Publications/Working_Papers/working/wor160.pdf (accessed on 15 September 2024).

Manasi, S., Latha N., Suhas Paranjape, Joy K. J., Nagothu, U. S., Raju, K.V., Mollinga, P. P., Doraiswamy, R., & Gondhalekar, D. (2009). Strategies and recommendations for river basin management in Tungabhadra STRIVER Report, No. D10.3, Available online: https://www.isec.ac.in/wp-content/uploads/2023/07/STRIVER_D10_3.pdf (accessed on 15 September 2024).

Marasini, K. P., Joshi, J., Yogi, B., Chhetri, D. R., Ghimire, A., & Shreshta, G. P. (2024). A Comprehensive Study on the Effects of Organic Fertilizers on Growth and Yield of Broad Leaf Mustard (*Brassica junceavar rugosa*) cv. Manakamana Rayo. *AgroEnvironmental Sustainability*, 2(1), 11-18, https://doi.org/10.59983/s2024020102

Maru, H., Haileslassie, A., & Zeleke, T. (2023). Impacts of small-scale irrigation on farmers' livelihood: Evidence from the drought prone areas of upper Awash sub-basin, Ethiopia. *Heliyon*, 9(5), https://doi.org/10.1016/j.heliyon.2023.e16354

Materu, S. T., Shukla, S., Sishodia, R. P., Tarimo, A., & Tumbo, S. D., (2018). Water use and rice productivity for irrigation management alternatives in Tanzania. *Water*, 10(8), 1018. https://doi.org/10.3390/w10081018

Merrey, D. J., & Lefore, N. (2018). Improving the availability and effectiveness of rural and "Micro" finance for small-scale irrigation in Sub-Saharan Africa: a review of lessons learned. Colombo, Sri Lanka: International Water Management Institute (IWMI). 46p. (IWMI Working Paper 185). https://doi.org/10.5337/2018.225

Mishra, K. C. (2023). Impact of Irrigation Management on Income and Employment of Members of Water Users' Associations of Puri District, Odisha. *International Journal of Innovative Research In Technology,* 9(10), 905-912.

Nakano, Y., Tanaka, Y., & Otsuka, K. (2018). Impact of training on the intensification of rice farming: evidence from rainfed areas in Tanzania. *Agricultural Economics*, 49(2), 193-202, https://doi.org/10.1111/agec.12408

Nations, U. (2015). Transforming our world: The 2030 agenda for sustainable development. New York: United Nations, Department of Economic and Social Affairs, *1*, p.41, Available online: https://sdgs.un.org/2030agenda (accessed on 04 January 2024).

Ngaiza, H. M. (2019). Irrigation management transfer: farmers' willingness to pay for operation and maintenance of selected improved smallholder irrigation schemes in Mbeya, Tanzania. Unpublished Doctoral dissertation. Sokoine University of Agriculture. (accessed 24 October 2024)

Ngango, J., & Seungjee, H. O. N. G. (2021). Adoption of small-scale irrigation technologies and its impact on land productivity: Evidence from Rwanda. *Journal of integrative agriculture*, *20*(8), 2302-2312. https://doi.org/10.1016/S2095-3119(20)63417-7

Ngene, B. U., Nwafor, C. O., Bamigboye, G. O., Ogbiye, A. S., Ogundare, J. O., & Akpan, V. E. (2021). Assessment of water resources development and exploitation in Nigeria: A review of integrated water resources management approach. *Heliyon*, 7(1), 1-10. https://doi.org/10.1016/j.heliyon.2021.e05955

Nkonya, E., Place, F., Kato, E., & Mwanjololo, M. (2015). Climate Risk Management Through Sustainable Land Management in Sub-Saharan Africa. In: Lal, R., Singh, B., Mwaseba, D., Kraybill, D., Hansen, D., Eik, L. (eds) Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa. Springer, Cham. https://doi.org/10.1007/978-3-319-09360-4_5

NMMI (2010). National Mission on Micro irrigation: operational guidelines. Ministry of Agriculture, Government of India, Available online: https://www.nccd.gov.in/PDF/Guidelines-NMMI.pdf (accessed on 10 February 2024).

NWP (2012). National Water Policy 2012. Ministry of water resources, Government of India, Available online: https://nwm.gov.in/sites/default/files/national%20water%20policy%202012_0.pdf (accessed on 20 March 2024).

OECD (2015). Organisation for Economic Cooperation and Development, Principles on water governance. OECD Publishing, Available online: https://www.oecd.org/cfe/regionaldevelopment/OECD-Principles-on-Water-Governance-en.pdf (accessed on 15 March 2024).

Ogunniyi, A., Omonona, B., Abioye, O., & Olagunju, K. (2018). Impact of irrigation technology use on crop yield, crop income and household food security in Nigeria: A treatment effect approach. *AIMS Agriculture and Food,* 3(2), 154-171. https://doi.org/10.3934/agrfood.2018.2.154

Ogwal, H. (2019). *T*he Right of Use and Economics of Irrigation Water in Uganda: A Comparative Analysis of Small-Scale Irrigation Schemes in Eastern, Northern and Western Uganda. Unpublished Master's thesis. Pan African University. Available online: https://repository.pauwes-cop.net/handle/1/332 (accessed 12 September 2023).

Olayide, O. E., Tetteh, I. K., & Popoola, L. (2016). Differential impacts of rainfall and irrigation on agricultural production in Nigeria: Any lessons for climate-smart agriculture?. *Agricultural Water Management*, 178, 30-36. https://doi.org/10.1016/j.agwat.2016.08.034

Oluwadare, O. S. (2014). Taungya farming-a strategy for sustainable land management and agricultural development in Nigeria. *Advances in Forestry Letters*, 3, 16-22. Available online: http://eprints.abuad.edu.ng/558/1/Taungya_Farming_-a_Strategy_for_Sustaina.pdf (accessed 12 September 2023).

Opio, M., & Mwesigwa, D. (2021). Embracing drip irrigation technology to stimulate smart farming: a study in Dokolo District, mid-north Uganda. *International Journal of Interdisciplinary Research and Innovations*, 9(2), 87-93.

Otoo, M., Lefore, N., Schmitter, P., Barron, J., & Gebregziabher, G. (2018). Business model scenarios and suitability: smallholder solar pump-based irrigation in Ethiopia. Agricultural Water Management – Making a Business Case for Smallholders. Colombo, Sri Lanka: International Water Management Institute (IWMI). 67p. IWMI Research Report 172. https://doi.org/10.5337/2018.207

Palanisami, K., Kumar, D. S., Malik, R. P. S., Raman, S., Kar, G., & Mohan, K. (2015). Managing water management research: analysis of four decades of research and outreach programmes in India. *Economic and Political Weekly*, 50(26/27), 33-43. https://www.jstor.org/stable/24482084

Paria, B., Pani, A., Mishra, P., & Behera, B. (2021). Irrigation-based agricultural intensification and future groundwater potentiality: experience of Indian states. *SN Applied Sciences*, 3, 1-22. https://doi.org/10.1007/s42452-021-04417-7

Parris, K., (2010). Sustainable management of water resources in agriculture. OECD Publishing. Available online: https://www.oecd.org/content/dam/oecd/en/publications/reports/2010/03/sustainable-management-of-water-resources-in-agriculture_g1ghc67c/9789264083578-en.pdf (accessed on 26 February 2024).

Rogers, P., & Hall, A. W. (2003). Effective water governance (Vol. 7). Stockholm: Global water partnership, Available online: https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/07-effective-water-governance-2003-english.pdf (accessed on 23 March 2024).

Rwanda IMP (2020). Rwanda Irrigation Master Plan. Rwanda Agriculture & Animal Resources Development Board, Republic of Uganda, Available online: https://www.minagri.gov.rw/fileadmin/user_upload/Minagri/Publications/Policies_and_strategies/Rwanda_Irrigation_Master_Plan.pdf (accessed on 10 March 2024).

Schrecongost, A. (2005). Irrigation Costs and Prices: An Institutional Economic Analysis of Pricing Strategies in the Office Du Niger and Small Pump-Irrigated Village Perimeters in Mali. Graduate Research Master's Degree Plan B Papers 11137, Michigan State University, Department of Agricultural, Food, and Resource Economics. Available online: https://ideas.repec.org/p/ags/midagr/11137.html (accessed on 10 March 2024).

Shankara, M. H., Vasudevan, S. N., Shreenivasa, K. R., Kumar, P. N., Shashikiran, A. S., & Desai, N. (2023). Impact of Capacity Building Programmes on Farmers of Hassan District of Karnataka, India. *International Journal of Environment and Climate Change*, 13(12), 1-6. https://doi.org/10.9734/ijecc/2023/v13i123654

Sikka, A. K., Alam, M. F., & Mandave, V. (2022). Agricultural water management practices to improve the climate resilience of irrigated agriculture in India. *Irrigation and Drainage*, 71, 7-26. https://doi.org/10.1002/ird.2696

Smeets, E., & Weterings, R. (1999). Environmental indicators: Typology and overview. Technical Report No.: 25, European Environment Agency. Available online: https://www.eea.europa.eu/publications/TEC25 (accessed on 20 March 2024).

Soumaila, A. (2021). Farmer-Led Irrigation Development in Niger. Water Global Practice Case Study. World Bank Publications, Available online: https://documents1.worldbank.org/curated/en/818351624267170265/pdf/Assessment-of-Farmer-Led-Irrigation-Development-in-Niger.pdf (accessed on 20 March 2024).

Sridharan, V., Pereira Ramos, E., Zepeda, E., Boehlert, B., Shivakumar, A., Taliotis, C., & Howells, M. (2019). The impact of climate change on crop production in Uganda—an integrated systems assessment with water and energy implications. *Water*, 11(9), 1805. https://doi.org/10.3390/w11091805

Streimikis, J., & Baležentis, T. (2020). Agricultural sustainability assessment framework integrating sustainable development goals and interlinked priorities of environmental, climate and agriculture policies. *Sustainable Development*, 28(6), 1702-1712. https://doi.org/10.1002/sd.2118

Teklay, G., & Ayana, M. (2014). Evaluation of irrigation water pricing systems on water productivity in Awash River basin, Ethiopia. *Journal of Environment and Earth Science*, 4(7), 70-76.

Theobald, B., & El-Sayed, N. B. (2019). Water Users Association and Irrigation Performance in Eastern Province of Rwanda. *Journal of Environmental Pollution and Management*, 2, 104.

UNDP (2014). Human Development Report. Sustaining Human progress: Reducing vulnerabilities and building resilience. New York, USA: United Nations Development Programme (UNDP), Available online: https://hdr.undp.org/content/human-development-report-2014 (accessed on 20 January 2024).

Van Koppen, B., Sokile, C. S., Lankford, B. A., Hatibu, N., Mahoo, H., & Yanda, P. Z. (2007). Water rights and water fees in rural Tanzania. In: Irrigation water pricing: the gap between theory and practice (eds F. Molle and J. Berkoff), International Water Management Institute, Wallingford, UK. pp. 143-163.

Vos, R. O. (2007). Defining sustainability: a conceptual orientation. *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology*, 82(4), 334-339. https://doi.org/10.1002/jctb.1675

Wamala, G., Bogere, M., & Angucia, M. (2017). Impact of agricultural modernization on the socio-economic status of smallholder farmers in Luweero and Nakaseke Districts in Uganda. *Nkumba Business Journal,* 16, 1-27.

Willoughby, R., Forsythe, L. (2012). Farming for impact-A case study of smallholder agriculture in Rwanda. *Farming for Impact*. Available online: https://gala.gre.ac.uk/id/eprint/12560/ (accessed on 20 January 2024).

Xie, H., You, L., & Takeshima, H. (2017). Invest in small-scale irrigated agriculture: A national assessment on potential to expand small-scale irrigation in Nigeria. *Agricultural Water Management*, 193, 251-264. https://doi.org/10.1016/j.agwat.2017.08.020